Journal of Coastal Research	SI 64	205 - 209	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Urban Coastal Flooding and Climate Change

J.J. Diez†, M.D. Esteban †, R. Paz‡, J.S. López-Gutiérrez†, V. Negro† and J.V. Monnot†

† FP7 SMARTEST Project Researcher.
Research Group on Marine, Coastal and Port Environment and other Sensitive Areas
Universidad Politécnica de Madrid, E28040, Madrid, Spain.
{josejavier.diez, mariadolores.esteban, josesantos.lopez, vicente.negro, jv.monnot}@upm.es

‡ FP7 SMARTEST Project Researcher.
Research Group on Marine, Coastal and Port Environment and other Sensitive Areas
Universidad Politécnica de Madrid, E28040, Madrid, Spain.
rosapaz@bio.ucm.es

ABSTRACT

Diez, J.J., Paz, R., Esteban, M.D., López-Gutiérrez, J.S. and Negro, V., 2011. Urban Coastal Flooding and Climate Change. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 205 – 209. Szczecin, Poland, ISSN 0749-0208

Coastal urban flooding is increasing, affecting mainly to new urban settlements but also to the traditional ones. This is due either to sea level and continental climatic factors. But also because population has increased at the same time being coastal areas selectively affected in old and new settlements, leading to need on flood resilience improvements The planet has been suffering a global warming change leading to sea level rise that is happening since the *Little Ice Age* although rising since 19th century. It comes with other synergic changes in marine and littoral dynamics, like *El Niño South Oscilation* and cyclonic storms. But other relative sea level movements are interfering in each segment of the coast with a local or even a regional character, being the main problem to discern the factors affecting these vertical movements This paper affronts the problem of the coastal urban floods, analyzing their increasing and variability, discussing the rebounds and the subsidence, discerning them from the global change in the long term, and the influence of other sea level changes in the "short term": meteorological phenomena (storm surge and set-up), wave set-up and other long waves, in order to allow a more accurate *Flood Resilience* measures.

ADDITIONAL INDEX WORDS: *Little Ice Age, global warming, sea level rise, coastal cities evolution, flooding risk, flooding types, resilience, FRE measures.*

INTRODUCTION

Processes of founding and expanding cities in coastal areas have undergone great changes over time. Populations have been driven by climatic conditions and they have moved in both latitude and altitude with changes in climate.

Flooding of coastal areas is today dramatically attributed to eustasic sea level rise caused by global climate change. This ascription can be somewhat inaccurate, however; even caused by the sea; it may not be by the sea level rise. The very concept of a coastal area is very imprecise, and can be understood in its broadest sense to apply to every territory that is directly subjected to climatic phenomena of a maritime nature. Using this definition, even most of the Mississippi Valley could be considered a coastal area.

Since the Little Ice Age (L.I.A.), the planet has been suffering a global warming change leading to sea level rise (S.L.R.). In the cycle-stochastic evolution of that change, the tendency has suffered several changes in its intensity and it is considered to be progressively increasing since the last quarter of the 19th century. The idea that it could be from anthropogenic origin had been due to Svante A. Arrhenius already in 1896, but it just was currently emphasized. But never before has the human factor been capable of having a significant influence on the climate. The discovery of fossil fuels, which allowed man to escape the tyranny of the climate, has had a destabilizing effect when combined with the ensuing qualitative increase in population.

Today we are experiencing this significant warming, many predictions for which seem to be ideological more than scientific, as often exaggerated and sometimes minimized. But this secular warming and the previous L.I.A. cold wave had precedents, always linked with changes in sea level. That is why the observation and investigation of signs associated with sea level change has always been a source of reference indicators for estimating past climates. It was precisely the obvious local signs of ancient levels, in the form of old beaches or dunes, or of fossils and submerged or elevated remains, some of them urban, which served to highlight past climate changes. They were soon assumed to have been caused by sea level changes in the nearest geological period. As the history of the planet was finely tuned other types of changes in sea levels became apparent, resulting from vertical movements of the earth's crust, modifications of sea basins due to continents fracturing, drifting and coming together, or to different types of climate patterns (Diez, 2000).

COASTAL CITIES VS FLOODING

Coasts in temperate climates with moderate or low humidity have allowed for earlier urban development. And structural coasts, especially if protected by some elevated orographic feature that affords a defensive stronghold, have favored cities more than those coasts of a sedimentary nature, for reasons of security, health and hygiene. But sedimentary coasts offer better conditions for agriculture and have attracted later a larger population. This apparent contradiction has been resolved through the selective settling of cities atop hills or on hillsides, or atop peaks or other elevated features of deltas and other littoral plains that are easy to drain and above flood levels. This is easy to see in the Mediterranean. Its seaside coastal cities ("maritime") are always next to a protective mountain (Athens, Haifa, Genoa, Monaco, Barcelona, etc.). In their absence, cities had to be built on drier and higher ground more inland (Rome on its seven hills, Valencia or Alexandria on their deltas, Venice on an interior relict barrier island of the ancient Po Delta).

The risk of flooding can never be eliminated, but only reduced to the extent possible. With time, as populations grew and expanded, cities were established in other climates, above flood levels and away from swamps and other wetlands whenever possible. The case of the city of New Orleans is paradigmatic: it barely suffered from Katrina's floods (Figure 1). No less typical is the occupation of the new Dutch polders in the 16th and 17th centuries (Beemster, Purmer, Vermer, Shermer…), which required significant modifications of the terrain to drain them. A prominent example was the delay in settling and colonizing the East coast of the United States during this time. By the time of the first permanent East American settling of Jamestown in Virginia coast, 1607, the entire continent, from Alaska to Tierra del Fuego, and especially its Atlantic and Pacific coasts, had already been occupied by Europeans but all East North American. The disappearing of Roanoake (NC, USA) shortly after its founding in 1586 suggests that this delay was caused by the high risk of flooding along that entire coast (Diez, 2001).

But no city has been able to limit its growth, and the systems for protecting against floods have not kept up with the pace of expansion of coastal cities. Enormous conurbations in the world today are at huge risk, mainly in deltaic areas of South and Southeast Asia, Sub-Saharan and equatorial Africa and the Gulf of Mexico. The great European delta formed by the Rhine, Meuse and Scheldt rivers has required drastic transformations in order to protect its many large cities (most of them on land reclaimed from the sea) from the risk of flooding, or to lessen it. The problems in all of these areas are not just from S.L.R. and associated climatic effects, but also due to subsidence and isostasy, which always affect these types of coasts, and which are exacerbated by the transformation of terrain and by settlements, by urbanization and edifications, and by the expansion of their cities into ever lower elevations. In every case in question, the cities have spread into areas below the probable average sea level if not originally founded there.

The current climate change is generating an upward trend in average sea level, but other regional and local factors result in this trend being accentuated in some places or attenuated, and even reversed, in others. Consequently, the intensity and frequency of coastal flooding around the planet originated from the ocean is increasing, although not so much as a unique result of this general eustasic elevation, but rather of the superposition of dynamic elements, also climate-related, which give rise to a temporary raising in average sea level in the short term.

Figure 1. New Orleans damages due to Hurricane Katrina

CLIMATE AND URBAN FLOODS

Climate can be considered the result of the functioning in the hydrosphere and atmosphere of complex thermodynamic "machine" whose temperature gradient is caused by the uneven heating via solar radiation of condensed surfaces (the earth's crust and oceans) on all areas of the planet, depending upon location and natural conditions. Subsequent radiation from these surfaces results in the consequently uneven heating of the atmosphere above them, along with the generation of convective movements and horizontal gradients producing the winds, displacement of air masses and the atmospheric circulation. Once the atmospheric dynamic is established as the first phase of climatic formation in its kinematics variant, its low pressure areas, more localized, cause surge in lakes, seas and oceans, which through resonance can give rise to seiches in inland or enclosed seas. At the same time, wind energy produces swells, set-ups and currents, resulting in the local, temporary rise of sea level and, consequently, the base level of the connected continental basins. Climate weather patterns are unpredictable, and are constantly changing over time and across the surface of the globe, as changes in the water cycle and atmospheric and oceanic dynamics are the "mechanisms" by which thermal balance is regained through an interactive process driven by uneven solar radiation. However this spatial-temporal variability is inherent to a stationary climate.

Thermodynamic changes in the global water cycle allow for the evaporation of surface water, and its precipitation on the surface of any area of the planet. Atmospheric dynamics determine, in turn, the spatial location of this precipitation as masses of air varying in humidity and temperature are displaced until processes of condensation are generated. Precipitation in the form of rain immediately triggers pluvial flooding (flash flooding when the intensity is extreme). If it continues upland or when snow and glaciers melt eventually fluvial flooding can occur. Continental precipitations start the hydrologic cycle, resulting in soil infiltration and surface runoff. At seaside areas and at their mouths rivers build littoral plains, in which the water subterranean flow can be comparable to the sub-aerial ones. The water levels near the sea and estuaries allow sedimentation of solids, producing alluvial and coastal plains in which the flow of subterranean water can reach levels comparable to strictly backshore rivers.

In this hydrological process featuring the transport of masses, the presence of urban land and landscape represent important, modifying factors: Filtration is reduced due to the relative impermeability of the soil. The quantity as well as the speed of runoff consequently increases regardless of the slope because there is less friction. Buildings become obstacles that creates damming, leading to localized flooding due to accumulation. Additional interference is caused by river and waste water drainage systems. River courses and their "floodplains" are often urbanized, increasing flooding and the rigidity of their banks and beds. Permeability, gradual or negative slopes, and the accumulation of water on free surfaces favour soil infiltration and cause, when the quantity of water is greater than its drainage capacity, pooling which can be considered a first way of flooding (groundwater). The accumulation and runoff of water on free surfaces can be considered the second, and the speed of runoff water can be considered the third.

The climate also influences water enclosed in basins and, widely, oceans and adjoining seas. Its dynamic affects sea levels in coastal areas, where tides as well as the structure and dynamic of the geoid and its crust come into play. From the sea, waters can flood and break or push back berms and other coastline borders. The sea level, controlling the mouth of the main channel of the basin's drainage system, is ultimately what governs flood levels. A temporary rise in sea level acts as a dam at the mouth. If these are urban, the little natural drainage through accentuates flooding. Types of flood damage vary depending on the location and characteristics of the urban area, affected by the nature and structure of the land.

Continental precipitation can occur very frequently under atmospheric conditions (hurricanes, extra-tropical cyclones, monsoons) of relative low pressure and/or with winds from the sea. This raises the sea level at the estuary and on the coast in the form of a storm surge, and the wind blowing from the sea causes additional (wind) set-up. Under these conditions coastal flooding from the continental side is accentuated by the rise of the drainage flow base level. Many floods like this are actually due to recent planning and development in which the variability of sea level is not properly taken into account; traditional knowledge of the territory had avoided the occupation of these areas. In fact, the S.L.R. process since the L.I.A. and other tectonic and subsiding processes have actually been acting in the same manner.

There exist coasts where several climate factors can simultaneously converge on flooding. The case of monsoonal flooding is an example: Monsoonal rains on the extensive coastal plains (structurally deltaic-coastal where Calcutta, among others is located) intensify the flooding caused by melting snow from the Himalayas. Drainage is influenced by the relatively low sea level, increased by the same winds and low pressure that cause the seasonal rains. It can similarly be seen under hurricanes and other low-pressure storms.

So, the question of living with floods became an aim in many coastal cities; and we can consider this process to be the origin of the concept of Urban Flood Resilience (Pasche *et al.*, 2007), which can be obtain not only through planning and building infrastructures, that in many cases may not be enough, but through different technologies and systems too. A way to improve Flood Resilient (FRe) technology is to reduce deficiencies and obstacles in the implementation of Flood Resilience Measures, facilitating the design of more holistic flood defense systems and supporting the implementation of the new flood risk management policies (DEFRA, 2007). This technology may be based on so called smart systems that incorporate sensor technology, automatic control, innovative materials and high levels of performance. This innovation will improve the effectiveness especially in the case of pluvial and flash floods where extreme short response time requires automatic deployment of Flood Resilience systems (Salagnac, 2006). Flood Resilience systems will substantially reduce the damage, the costs and the health impacts associated with flood hazards.

CURRENT WARMINGS VS CLIMATE CHANGE

The first consequence and initial cause of climate change which draws interest on a global level are the S.L.R. and CO_2, respectively, not so much due to Arrhenius's arguments (1896), but rather as a result of much later observations as Bruun's (1962). And the alarm factors are due, primarily after 1970 Club of Rome meeting, to the use of the three now famous scenarios posed by Hicks (1973). The current warming period started after the L.I.A., in the mid 19th century. In spite of the obvious Arrhenius explanation, the difficulty in accurately determining its chronology remains, however. Depending on the object of study and on its relevant climate parameters, the times for the beginning and end of the L.I.A. differ.

The mechanisms causing the planet to warm are based on the often misunderstood greenhouse effect. And Arrhenius (1896) had established a logical chain which goes beyond the mere impact of the greenhouse effect on temperature: 1) Solar radiation is the cause of "ambient" planetary warming through its surface pre-heating and subsequent subordinate radiation at a greater frequency. 2) This "ambient" temperature melts continental surface ice on the planet, increasing the mass of water in the sea (today we would have to qualify that it also dilates it), and, as a direct result, the level of its basins. 3. Consequently, all other factors being equal, the burning of fossil fuels demanded by the industrial revolution had to result in a rise in average relative sea levels. This clear statement was overlooked for almost seventy years in general terms however.

More relevant were the multiple works by Fairbridge (1983) since before 1961 discerning eustasic changes from other attendant causes, and by Mörner stressing the effects of geoid changes and rescuing Milankovitch's "forgotten theory" since even before 1976, the last itself a consequence of a thorough understanding of both the Arrhenius "doctrine" and the relative movement of the Earth's surface with respect to the Sun, which enabled him (1930) accept the significant role of solar activity and of the modulating effects the three components of said movement have on its radiant effects, to explain in 1927 the four great waves of quaternary glaciations. Such a theory is capable of explaining with surprising accuracy not only the four glacial cycles generally referenced, but up to the nine sometimes described and other significant oscillations within them. But it cannot explain all or most of the stoppages and reversals of their associated processes.

All of these must be considered as forerunners to the natural component of current Climate Change. Its changes and those of sea level, on a time scale from decades to centuries are going to establish the natural environmental conditions of the future, giving more importance still to a precise knowledge of its origins and possible recurrence. Today the nature of solar activity is better understood and data are available to deduce its influence on climatic cycles over minor periods. We can perhaps lament the fact that they are not receiving the general attention that they deserve by expert panels. It seems that we are also reluctant to fully recognize the influence of the hydrosphere on climate, or the fact that the role of oceans has not been completely incorporated into coupled models. In them, ocean climate phenomena are seen as just consequential, when they are also causal factors, as the outcome of the Atmospheric-Oceanic Thermal Machine.

RECORD OF SEA LEVEL

The conceptual process of discerning the various mechanisms linking climate to (relative average) sea level, as attributed especially to temperature but also to other associated factors, is advancing relatively slowly. Eustasy was initially restricted to account for the change of state from water to ice, and it took time to realize the existence of a steric factor (Fairbridge, 1983). In a strict sense, both temperature and salinity affect density, and not always in the same way since other local factors are also at work, some of them also climatic and different from temperature. It took even longer to consider the effects of tectonics (Lisitzin, 1974), isostasy (Peltier, 1999) and geoid deformations (Mörner, 1976) on the capacity of sea basins through the modification of their shapes. Most of these factors can be considered independent, though they sometimes exhibit dialectic collective or compensatory characteristics. Finally, we must be aware that, contrary to what subsidence models seem to assume, glacial rebound or readjustment is not the only significant source of isostasic subsidence.

Above all we must bear in mind that historical sea levels are relative to some level on a nearby coast, and therefore local (altimetry allows for absolute determinations but they are still insufficient); that certain long-standing levels can differ notably from real average levels once brief changes are accounted for, and lead to errors in the trend analysis; and that the global average sea level requires a statistical treatment of historical data on a secular level to allow for a trend analysis that will enable short-term (less than a year) cyclical oscillations to be filtered out as noise. The relevance of this point is that the average relative sea level has been the most important piece of data for estimating the planet's climatic condition, only tempered following the intervention of a complex subsidence process.

A heating process must in fact be followed by a rise in ocean surface level, but since said rise could only be determined in reference to the elevation of a fixed point on the crust's surface, any modification of the crust affects that of the ocean and its variation. Hence the importance of a measurement system in the future that can account for the impact of these crustal movements, both vertical ones that affect the elevation itself, as well as horizontal ones that, by modifying the sea basins, affect their water-holding capacity. Also important is the ability for the maximum possible discrimination when analyzing the various causes and types of crustal movements, and calculating their magnitudes as accurately as possible. Diverse records from different areas of the planet point to variations of different natures significant versus eustasy in both senses. The development of methods for the analysis of sea level records is allowing, not without some effort, for a progressively reliable revision of values estimated in the past, after having served to trigger the alarm about the effects of Climate Change. Critical reflection (Emery and Aubrey, 1991) has led to a more prudent attitude, one that, while not predominant, is still encouraging.

CONCURRENT FACTORS ON SEA LEVEL

The average sea level is determined for a specific place, time and sea state, and varies in the short and long term with changes in the oceans and with crustal movements. Altimetry techniques are already being used, but historical data sets are based on tidal gauge records, or on even less precise historical-geo-morphological observations, mainly aiming to establish an average global sea level over time; this parameter being associated with the thermal and climatic state of the planet through Eustasy, which aims to account for the simultaneous vertical shifts of the sea surface all around the planet. The effect of climate is through ambient temperature, which affects the melting of ice caps and the density (volume) of ocean waters. But the geological condition affects the capacity of the oceanic basins, and geoidal changes the geo-potential surfaces due to various mechanisms, even linked to climate itself (Mörner, 1976). Although not everyone admits such complexities in the eustasic phenomenon, the fundamental problem lies in distinguishing it from concomitant phenomena (Paskoff, 1985).

In addition to its eustasic effect, tectonics and volcanism force local changes in relative sea level through the vertical movement of certain portions of the crust. Changes along the edges of converging plates tend to be faster and more abrupt, whether positive or negative. Along diverging plates they tend to be slow and around 1mm/year negative, which would be equivalent to between 1/2 and 1/4 of the total change along the eastern coast of the United States. Tectonic phenomena are slow and difficult to detect, and are thus lumped under the category of subsidence.

Isostatic changes are vertical movements in crust plates due to the Archimedean principle of buoyancy. Depending on their immediate causes, they can be glacio-isostatic, hydro-isostatic, erosive or sedimentary. Along with these, there are at least four other vertical movements which extend to the crust's surface and which, unable to be distinguished, are lumped in the subsidence category (Diez and Arenillas, 1982): strict isostasy, positive or negative depending on whether the load on the tectonic plate is increased or lessened, in which sediments are the primary cause of the former and the melting of surface ice the cause of the latter; indirect isostasy, caused by the bending, if present, of the plate affected locally by the preceding; that caused by the natural consolidation of sediments under their own weight; and that caused by the anthropogenic compression of sediments, either by drainage or under load. This last category is associated with the loss of interstitial fluids (water, gas or petroleum), as in Venice (Figure 2), and has been highlighted along the coasts and beaches of Denia, (Alicante, Spain) (Figure 3). Its analysis and scope is complicated depending on whether it involves a submerged or emergent surface, or alternates. The key factor to consider in all of these subsidence processes is that of inertia or the delay with which they are produced starting from the initial cause which triggers them.

Meteorological variations in sea level due to friction by the wind (wind set up) and barometric depressions (storm surge) are inversely proportional to depth, and therefore they are especially pronounced along flat coasts and shallow seas. Climate also

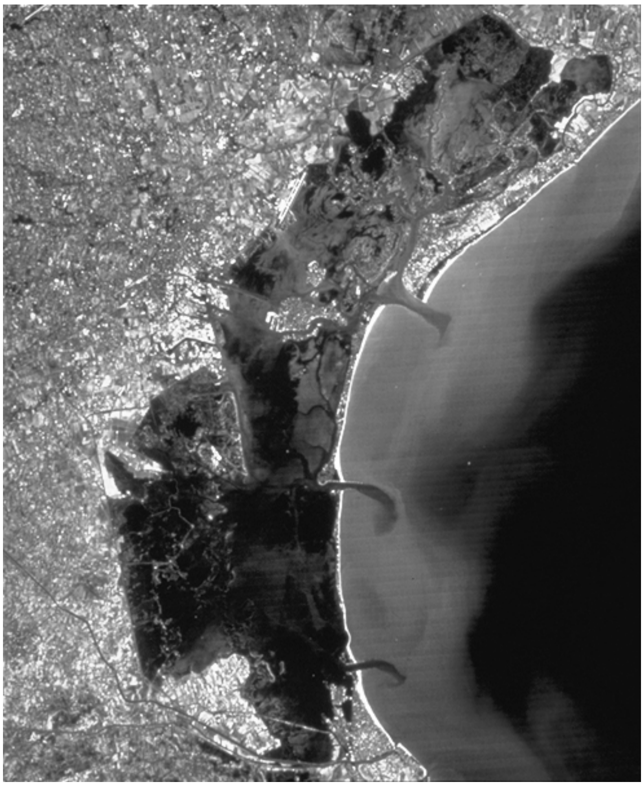

Figure 2. Venice aerial view (Source: Venezia Nuova).

Figure 3. Coast close to the city of Denia (Alicante, Spain)

affects the surge level and the wave set-up and breaking, greatly increasing its ability to transform the equilibrium profile and continental penetration of marine water. The climate also produces elevations due to wave set-up or wave run-up. The former can lead to water cresting over dikes or other defenses, resulting in temporary flooding. The morphology of the location and the drainage conditions can make it more prolonged, and even maintain a residual flooding level above the average level as determined by other factors. That may have been the case in New Orleans (La, USA) in 2004. These effects are accentuated if the surge takes place at shallow depths and is already accompanied by a certain mass transport in the direction of propagation. Moreover and alternatively, it is impossible to ignore the value of maximum wave run-up, which could be more detrimental, especially keeping in mind that one of the effects of this excessive elevation is the breaking or piercing of the onshore barrier that protects the littoral plain from flooding. The breaking wind waves modify the shape of the equilibrium profile of the ocean bottom, and can shift the coastline inland. In this way it can even compromise the natural barriers that enclose certain littoral lagoons, as has happened several times in Galveston (TX, USA). Penetration due to run-up involves a small volume of water and a limited duration per wave, thus restricting its damage.

CONCLUSSIONS

Urban expansion on coastal zones has been increasing by population grown and displacement; and the process itself is highly increasing during last century.

Climate, for its part, has been changing in the sense of coastal flooding growing, through both sea level rising and several meteorological phenomena accentuation.

Other longer term local/regional coastal changes, most occasionally favoring floods, interfere leading to more frequent and intense flood risks and damages.

Planning may help to improve resilience in many cases, especially in new settlements; and infrastructures can do it in many other cases; but in most of them may be necessary other measures, as FRe Technologies and Systems. Better knowledge appears to be necessary to make the design of more holistic flood defense systems easier and to support the implementation of new flood risk management policies.

A first question, then, is to distinguish between S.L.R. and the average specific S.L. variation along any given coast. This requires, first and foremost, a correct determination of the average sea level at any coastal point.

A second issue is to distinguish between the possible causes of general S.L.R. due to global change. The role of solar activity, the greenhouse effect and biogeochemical activity in the oceans has yet to be satisfactorily discerned.

A final question is to improve the knowledge of the performance of different resilience technologies, products and systems.

LITERATURE CITED

Arrhenius, S., 1896. On the Influence of Carbonic Acid in the Air upon the temperature of the Ground. *Philosophical Magazine and Journal of Science,* Ser. 5, Vol. 41, Nº 251.

Bruun, P., 1962. Sea Level Rise as a Cause of Shore Erosion. *Proceedings ASCE, Journal, Waterways and Harbor Division*, Vol. 88, 117-130.

DEFRA, 2007. Flood resistance and resilience solutions: an R&D scoping study. R&D Technical Report.

Diez, J.J. and Arenillas, M., 1982. Littoral Processes in Denia Coasts. *Proceedings S.E.M.E*, pp. 1.81-1.95.

Diez, J.J., 2000. A review of some concepts involved in the sea level rise problem. *Journal of Coastal Research,* Vol. 16(4), 1179-84.

Diez, J.J., 2001. Climatic versus Geomorphologic Changes: influence on Landing Processes in Eastern Coasts of North America. *Journal of Coastal Research,* Vol. 17(3), pp. 553-562.

Emery, K.O. and Aubrey, D.G., 1991. *Sea Levels, Land levels, and Tide Gauges*. Springer-Verlag New York.

Fairbridge, R., 1983. *Isostasy and Eustasy*. D.E. Smith et al (ed). Shorelines and isostasy. Institute of British Geographer. Academic Press. London.

Hicks, S., 1973. *Trends and variability of Yearly Mean Sea Level 1893-1971*. Noaa Technical Memorandun nº 12, U.S. Dep. of Commerce.

Lisitzin, E., 1974. *Sea Level Changes: Amsterdam*. Elsevier, 286p.

Milankovitch, M., 1930. *Mathematische Klimalehre und Astronomische Theorie der Klimaschwankungen*, Handbuch der Klimalogie. Band 1. Teil A Borntrager. Berlin.

Mörner, N.A., 1976. Eustasy and Geoid Changes. *Journal of Geology*, 84 (2), pp. 123-151. & (1995). Sea Level and Climate-The Decadal-to-Century Signals. *Journal of Coastal Research Special issue Nº 17: "Holocene Cycles" 2: (Climate, Sea Levels, and Sedimentation),* pp. 261-268. Florida.

Pasche, E.; Zevenbergen, C.; Garvin, S.; Ashley, R., and Vassilopolos, A., (2007). *Advances in Urban Flood Management*. Taylor and Francis Group.

Paskoff, R., 1985. *Les littoraux - impact des aménagements sur leur évolution*. Col. Géographie, Paris, Masson, 185 p.

Peltier, W.R., 1999. Global sea level rise and glacial isostatic adjustment: an analysis of the data from the east coast of North America. *Geophys. Res. Letters,* 23, 717-720.

Salagnac, J.L., 2006. Rendre les bâtiments moins vulnérables aux risques naturels. *Annales des Mines, Responsabilité et Environnement 43, Catastrophes et Territoires*, 47-52